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Introduction

What are clouds? The answer to that question is both obvious and subtle. In the terrestrial atmosphere clouds are familiar as vast collections of small water drops or ice crystals suspended in the air. In the atmospheres of Venus, Mars, Jupiter, Saturn, Saturn's moon Titan, Uranus, Neptune, and possibly Pluto, they are composed of several other substances including sulfuric acid, ammonia, hydrogen sulfide, ammonium hydrosulfide, methane, and complex organic molecules. The study of clouds touches on many facets of atmospheric science. The chemistry of clouds is tied to the chemistry of the surrounding atmosphere. Clouds can be both a source and a sink for condensable molecules as they moisten or dry the air. Local cooling or heating and local differences in moisture content due to cloud formation change the buoyancy of air parcels which drives local dynamics (frontal systems, thunderstorms and hurricanes are a few familiar examples). Clouds influence the global climate by reflecting or absorbing solar radiation while trapping thermal radiation. The fate of life on Earth a few centuries from now may hinge on their uncertain role in mitigating the greenhouse effects of increased emission of carbon dioxide gas from biomass and fossil fuel burning. This article examines what we know about clouds in the atmospheres of the planets.

Cloudy planetary atmospheres

Saturn's largest satellite Titan and all the planets except Mercury have cloudy atmospheres. These can be categorized into three main groups. Water is the principal cloud constituent on the relatively thin atmospheres of Earth and Mars. Venus and Titan have thick cloud and haze layers which are influenced strongly by chemical reactions initiated by sunlight in the high atmosphere. The giant planets Jupiter, Saturn, Uranus and Neptune have reducing atmospheres dominated by hydrogen which combines with trace amounts of nitrogen, sulfur and carbon to form clouds of ammonia (NH_3), ammonium hydrosulfide (NH_4SH), hydrogen sulfide (H_2S) and (for Uranus and Neptune) methane (CH_4). Methane clouds were inferred to be present in Pluto's atmosphere although the interpretation of the data is ambiguous.

The Earth

We know most about the nature of clouds in the Earth's atmosphere and so it is instructive to begin a survey of planetary clouds with a review of terrestrial clouds. Water is by far the main constituent of terrestrial clouds but some other constituents (mainly sulfur and nitrogen) are often present. Water can exist as vapor, liquid drops, or frozen ice crystals. The amounts of water in these various forms depends on the complex history of each air parcel as it moves over land or water. Clouds take on characteristic forms which are controlled by the dynamical processes responsible for their formation. By looking at photos of clouds taken from space a sense of the dynamical regime can be revealed.

Visual categorization of cloud types is a science that goes back many hundreds of years, and much of the terminology is Latin. Meteorologists in the present day group clouds into three main groups depending on the altitude (low, middle and high), with sub-categories within each group. In the lowest 2 km altitude are the cumulus, cumulonimbus, stratus, stratocumulus, and nimbostratus. Within the middle layer (2–8 km) are altostratus and altocumulus. At the highest level in the troposphere are cirrus, cirrostratus and cirrocumulus. At still higher altitudes in the stratosphere and at very low concentrations (except immediately after a volcanic eruption) are small sulfuric acid drops at many latitudes and ice particles which form the polar noctilucent clouds (thin clouds seen in the polar dawn and dusk).

Cumulus clouds are relatively small (a few km in diameter), detached, puffy clouds whose tops and sides appear brilliant white in direct sunlight. In this form they would be impossible to see from space unless observed with a nearby camera with high spatial resolution. They can be seen as single clouds, in fields of many, and may develop into large towers of several grouped together. As moisture becomes more available from ground evaporation these clouds can grow and merge to form cumulonimbus which are heavy and dense, with a towering structure. These can be sites of precipitation and lightning. As seen from above they often show a flat top with a tail extending downwind. The morphology of the tail appears similar to a blacksmith's anvil, and the word 'anvil' is often applied to these features. The clouds are classified as low clouds because the base is within the lowest level, but in its entirety the cloud extends through all three levels, with the anvil providing a source of water downstream in the highest level.

Stratus clouds form a fairly flat, uniform layer, dark gray blanket when seen from below. They often produce drizzle or snow. Stratocumulus appear much like stratus except that they show detail (patchiness, ragged edges) and are less dense in places, permitting more sunlight to penetrate and showing a lighter shade of gray. Seen from above, they appear clumpy and sometimes reveal periodic roll structures (cloud streets) which can extend for many kilometers. Motion within these clouds can occasionally produce cumulus-type structures. Large (~1000 km) banks of stratus and stratocumulus clouds can be seen in satellite photographs. Nimbostratus can be extremely deep with a top nearly at the top of the troposphere and usually produce precipitation.

Altostratus clouds are distinguished from stratus mainly by the location of their base which is higher in the troposphere. A colored corona around the Sun can sometimes be seen. This is a consequence of the way ice crystals scatter light. Altocumulus also have their base higher in the atmosphere compared to cumulus. These clouds are usually thin and may take on a multitude of forms from thin and flat to detached clumps to castle-shaped morphology.

Clouds in the high troposphere are composed almost entirely of ice particles. By analogy with the lower clouds, the clouds which are confined to the highest layers (cirrus, cirrostratus, and cirrocumulus) can range from broad flat sheets to clumpy, distinct elements. There are many sub-categories of cirrus which characterize the many ways these clouds can appear (smooth, stranded, with hooks, in cells, grainy or undular, resembling skeletal structures, etc). All of this morphological richness is rooted in the equally rich dynamic wind field and a complex interplay between the supply of vapor or crystals, and cloud microphysical processes (nucleation, condensation, growth, evaporation, aggregation, precipitation). Much of the cirrus owes its origin to water supplied by high altitude entrainment of air from upstream cumulonimbus anvils and nimbostratus cloud tops. Atmospheric halos and coronae are often seen within thin cirrus clouds, a result of sunlight scattered by large water ice crystals.

How do we understand the complexity of the different cloud types and what do they tell us about the processes? This is an area of active research but already a great deal is known. The existence of a cloud points to a process where an air parcel containing water vapor (say, from evaporation over the ocean or over moist land surface) was transported to a location where the temperature is cooler—cool enough that the vapor pressure of water in the air is higher than the condensation vapor pressure at the air temperature. In the lowest 12 km or so altitude (the troposphere) the temperature decreases with altitude, so a parcel of moist air which buoyantly rises from the ground will eventually reach a level where the temperature is cool enough to support condensation and cloud formation. Low-lying clouds have so much moisture that they need not rise very far for the temperature to reach the condensation temperature. Another way to cool the air and promote cloud formation is to mix warm moist air with cool dryer air as a polar cold front moves through. A third way is to lift air as it flows over a mountain. A cloud forms above or nearby a mountain when the air flowing over cools as it reaches a higher altitude. Clouds formed in this way are called orographic clouds because they remain fixed next to a topographic feature as the air flows past. The same process operates in the Martian atmosphere near the tops of the high volcanos and in Neptune's atmosphere above a large vortex (the Great Dark Spot).

Cumulus cloud formation is initiated by natural convection as sunlight warms a moist ground. As a warm, moist buoyant parcel of gas rises it reaches a condensation level where the temperature drops below the condensation temperature and the cumulus cloud forms at its base. An aid to convection in the terrestrial atmosphere is the density difference due to both the temperature difference (a warm parcel is less dense) and a compositional difference (a moist parcel is less dense than dry gas for the Earth's atmosphere). In the giant planet atmospheres a moist parcel is more dense than dry gas which inhibits rather than promotes moist convection. A third factor which enhances moist convection is the additional heat released as latent heat of condensation when the vapor condenses in the cloud. In a quiescent situation where cumulus or stratus clouds form and dissipate at an equal rate there is an equilibrium between the supply of moist air from the ground and evaporation and precipitation in the cloud. If there is a great deal of moisture available from the ground and if the initial convective motion is quite vigorous an instability can grow, with the buoyancy carried by the moist convective parcels amplifying to the point that very large amounts of moisture are injected at very high altitudes (cumulonimbus towers and anvils). Stratus clouds result from a more sluggish dynamical regime where the air is more stable and where there is a stable and abundant supply of moisture to maintain the cloud against precipitation and evaporation.

Space-based views of clouds on all the planets are dominated by the large-scale features. At large scales three types of cloud features are commonly seen in the Earth's atmosphere. Each of them has an easily recognizable morphology and motion which are rooted to the dynamical regime forcing cloud formation. Mesoscale convective systems consist of fields of cumulonimbus clouds whose anvils merge into a single cloud shield with a horizontal extent much larger than the individual anvils. Mesoscale convective systems may be long (~100 km) and narrow (a few km) with extensive precipitation occurring over a large scale. *Cumulus convection* is driven by small-scale (100 km or less) convective cells. Small-scale cells can combine to form the much larger mesoscale convective systems seen in satellite images.

Of special importance for the dynamics of the terrestrial atmosphere is the organized deep convection near the equator. Time-averaged maps of cloudiness reveal a band near the equator that moves in latitude with the seasons. This is the Inter Tropical Convergence Zone (ITCZ). Its existence is prompted by converging air mass at low altitude driven by large-scale Hadley circulation in both hemispheres. Abundant water vapor near the surface is available for a massive amount of latent heat transport. Moist convection within the ITCZ is vigorous and is responsible for a large amount of heat and moisture transferred to the upper atmosphere within the ITCZ.

Atlantic hurricanes and Pacific typhoons are tropical cyclones which constitute another commonly observed large-scale cloud structure. They form over oceans and derive their energy from moist warm tropical ocean air. Cyclones rotate in the counterclockwise direction in the northern hemisphere with lifetimes of the order of 10 d. Hurricanes and typhoons have return flow in a narrow column at the core which is free of clouds. There remains some controversy about what special conditions are required to transform commonly occurring tropical cyclones into intense systems that occur relatively rarely. A common thread to the various models involves a very effective coupling between cumulus-scale moist

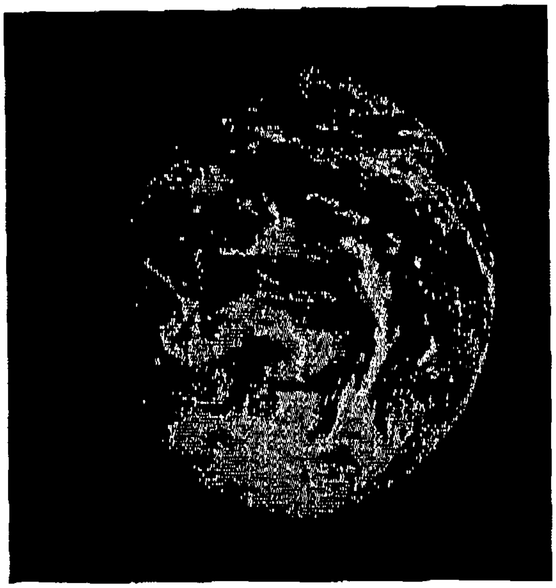

Figure 1. The Solid State Imaging camera on the Galileo Orbiter captured this image of clouds over the southern Pacific ocean and Antarctica on 12 December, 1990 when the spacecraft was 1.6 million km from Earth. Extensive cloud formation can be seen, with prominent curved cloudy frontal systems associated with extratropical cyclones. The dark ocean provides the contrast which makes the clouds easy to see in visible-wavelength images. Clouds and surface ice are difficult to distinguish due to lack of contrast. In broad-band visible wavelengths there is no way to get a sense of cloud altitude, and the cloud type categories developed from ground-based experience are not apparent.

convection with the large-scale wind field via an instability called the conditional instability of the second kind, or CISK. According to most models the ocean surface temperature must be at least 26 °C, which agrees with observation and leads to the conclusion that these intense storms will be more frequent and/or more intense should the sea surface warm in the future from global warming.

A third commonly observed large-scale cloud structure is the extratropical cyclone which produces extensive precipitation in the middle latitudes. Several of them can be seen in figure 1. They are familiar as weather fronts ahead of cold low-pressure regions. The clouds that form at these fronts do so by *sloping convection* (as opposed to cumulus convection described above). Sloping convection occurs when one body of air overrides another, forcing moist air upward. Clouds of all types are associated with these large-scale features and also with the two others mentioned above.

With that brief introduction to terrestrial clouds we are now in a position to explore clouds on other planets. The best place to begin is with the atmosphere of Mars which contains water ice clouds and displays many of the dynamical features familiar to terrestrial meteorology.

Mars

Our knowledge of the Martian atmosphere is based on images and spectra taken over many years from ground-based observatories as well as the Hubble Space Telescope, several Soviet and US flyby or orbiting satellites, and landers, most notably Mariners 4, 6, 7 and 9, Mars 2, 3, 4 and 5, Viking 1 and 2, Phobos 1 and 2 and Mars Global Surveyor, with more on the way or planned. As of the beginning of 1999 three craft (Viking Landers 1 and 2 and Mars Pathfinder) have landed on the surface and sent back *in situ* information on atmospheric composition, temperature, pressure and cloud and dust opacity. Many more landers are planned for the next decades.

The Martian atmosphere is made up almost entirely of carbon dioxide (CO_2) with trace amounts of water, argon and several other constituents. Mean surface pressure is 8 mb (compared to a pressure near 1 b at sea level on Earth). Surface temperature varies between about 140 K and 250 K depending on latitude and season. Carbon dioxide condenses to form an extensive frost layer on the surface of Mars at high latitude when the surface temperature drops slightly below 150 K. Occasionally the temperature in the polar atmosphere several km above the surface drops low enough to form a CO_2 ice haze, but almost all the bright white clouds seen on Mars are composed of water ice.

Water ice also condenses at high latitude during winter, and at lower latitudes as well during the cold night. The polar ice caps and the Martian soil serve as reservoirs of water which absorb or release water on diurnal and seasonal cycles as well as on much longer-term cycles tied to slow changes in the Martian orbit and tilt. Outflow channels on the surface are now dry but point to a much wetter Mars in the distant past. The present amount of water in the atmosphere amounts to only about 10 precipitable micrometers on average, too little to be important as a source of buoyancy via latent heat release. Thus none of the terrestrial cloud types (cumulonimbus or stratonimbus on the small scale, hurricanes and mesoscale convective systems) which feed on latent heat release and an abundant supply of water are seen on Mars.

The most fruitful approach to understanding water clouds on Mars is to note their similarity to cirrus clouds in the high, cold terrestrial atmosphere, with the addition of the effects of topography operative in the Mars atmosphere. Lee wave clouds are often seen on Mars downstream of high volcanic mountains and near craters at lower elevations. It is common to see lee wave clouds with many linear undulations extending for more than 100 km downstream. Clouds form most often in the early morning and late afternoon when the temperatures are cool. They are abundant in northern summer in the Tharsis region, a high plateau home to several of the highest Martian volcanos. Figure 2 shows this, along with large-scale features that appear to trace planetary-scale Rossby waves at high latitude much as do extratropical cyclone cloud bands on the Earth. At night the surface can radiate to space efficiently and cool dramatically, leading to the

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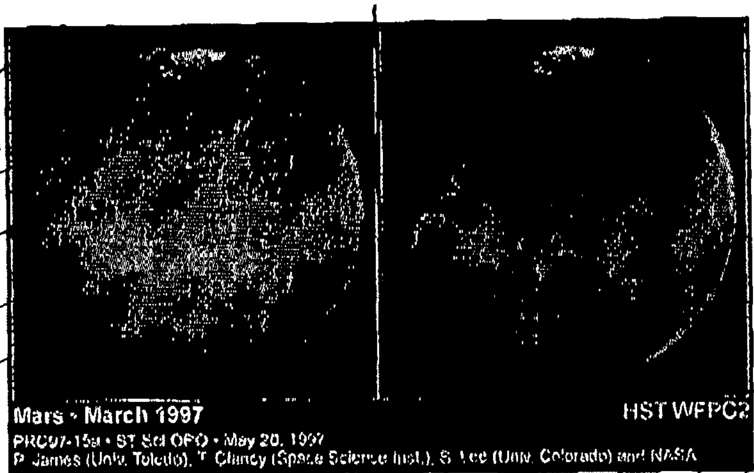

Figure 2. The surface of Mars is dark at blue wavelengths and produces a good background for showing bright water ice clouds and north polar frost deposits seen in this image taken by the Hubble Space Telescope Wide Field and Planetary Camera 2 on 20 May, 1997. Features as small as 45 km can be seen. Ice clouds cover most of the Martian mid-latitudes and are especially prominent in the Tharsis Montes region to the left of the center of the planet. Four of the highest volcanic peaks can be seen poking though the clouds. The curved cloud contours in the upper left are suggestive of planetary-scale waves similar to those which drive large extratropical cyclones in the terrestrial atmosphere. (Photo courtesy of P. James, T. Clancy and S. Lee.)

formation of low-lying ground fog which dissipates soon after sunrise.

Although not classified as cloud, dust in the Martian atmosphere plays an important role in atmospheric dynamics and cloud formation. The Martian atmosphere usually contains enough dust to be a significant absorber of solar energy, heating the atmosphere during the day and promoting radiative cooling at night. Strong thermal contrasts at the edge of the polar frost deposit, coupled with the low density of the Martian atmosphere, can lead to high surface winds which pick up dust, sometimes progressing to a global dust storm that can blanket the planet, obscuring even the highest volcanos. After several months most of the dust sediments out and the atmosphere gradually returns to a cooler state more conducive to the formation of water ice clouds.

Venus

Venus and the Earth have similar size and mass but their atmospheres and cloud structures differ markedly. The Venus atmosphere is composed primarily of CO_2. It is massive (90 bars at the surface) and hot (740 K) near the surface. Because of its great fluid mass, slow rotation and greenhouse effect there is little horizontal thermal contrast (at most a few K from equator to pole) and consequently the dynamical regime is quite different than on the Earth or Mars.

Venus as seen through a telescope appears bright and almost featureless due to a ubiquitous thick layer of cloud. Subtle contrasts can be seen at violet and near-ultraviolet wavelengths. The material responsible for the contrast has not been identified with confidence but suggested candidates include elemental sulfur and the compound $FeCl_3$. Sulfur dioxide gas (SO_2) has been detected at the cloud tops, and the visible clouds are composed of liquid sulfuric acid (H_2SO_4) drops. At near-infrared wavelengths there are several spectral intervals (windows) where the gas opacity is relatively low, permitting infrared light radiated by the hot surface to penetrate the clouds. There is considerable cloud opacity even at those wavelengths however, so the contrasts seen in the near-infrared tell us mostly about the patchiness of the lower cloud layers which are more turbulent than the upper layer we see at visible wavelengths. These contrasts can be seen in figure 3.

Many spacecraft from the United States and the former Soviet Union have visited Venus. Several probes have descended into the atmosphere and measured pressure, temperature, gas composition, the internal radiation field and cloud particle number densities and sizes. The clouds extend over a very large vertical range. There are three main cloud layers at altitudes between about 45 and 70 km. Thin haze layers extend above and below those boundaries. Several experiments revealed the main cloud region to be composed of three layers. The top layer is concentrated between 59–66 km altitude. The middle layer lies between 49–57 km altitude and the lower layer is most dense in a 2 km region just below the 49 km boundary, at least as measured by the particle counter data on the Pioneer Venus large probe. Ground-based and Galileo near-infrared images (from the Near-Infrared Mapping Spectrometer—NIMS) later showed this layer to be highly variable in space and time (see figure 3).

The composition of the cloud particles is dominated by sulfuric acid, but some evidence suggests that an additional constituent may be responsible for the largest

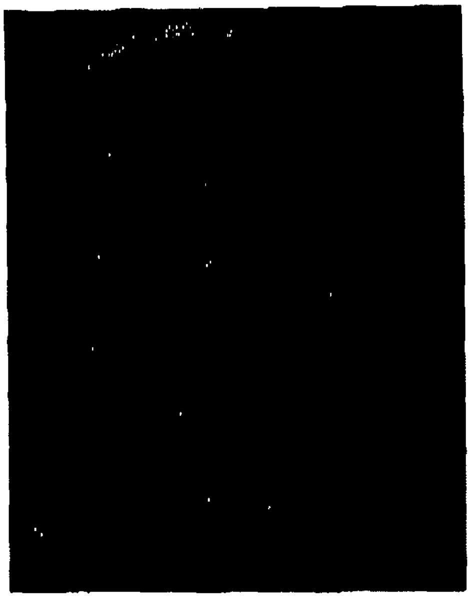

Figure 3. This image of the Venus nightside taken by the Galileo Near Infrared Mapping Spectrometer instrument at a wavelength of 2.3 microns in the near-infrared is bright where infrared light emitted by the hot surface is less attenuated by overlying clouds which block the radiation in the darker regions. The contrasts are produced mostly by variations in the number of large particles in the deepest of the three main cloud layers. These variations are due to atmospheric motions which are most vigorous in the lower cloud region.

particles in the lower cloud layer. In the top cloud and haze sunlight breaks up SO_2 molecules which combine with water to form sulfuric acid with a concentration near 85% at the top, increasing at deeper levels. In the middle and lower clouds there is insufficient ultraviolet light to drive photochemistry and thermochemical processes become important in establishing chemical equilibrium. At the deepest levels the atmosphere and surface interact and the surface acts as a source and sink of sulfur and other constituents. The particle spectrometer on the Pioneer Venus large probe identified three sizes of particles. Mode 2 particles have radius close to 1 micron and dominate the top and middle clouds. Mode 1 particles are smaller (0.4 microns mean radius) and account for a few tenths of the optical depth in the upper cloud while mode 3 particles are larger (several microns or more) and provide much of the mass in the lower cloud.

The dynamical regime under which these clouds form is mostly stable in the upper two layers (altitudes above 49 km). These clouds are analogous to stratiform clouds in the terrestrial atmosphere. The subdued contrasts seen in the highest cloud move with the wind speed (about 100 m s^{-1}) at the visible cloud tops (near 70 km altitude) while the contrasts seen in the near-infrared window regions (e.g. figure 3) move at a slower rate (50 m s^{-1}, consistent with wind speeds measured by tracking entry probes). Estimates of the number of large particles in the lower cloud deck made by various entry probes varied by large factors. This observation supports the idea that the contrasts seen at near-infrared wavelengths are indicative of highly variable concentrations of large (several microns radius or larger) particles in the lower cloud deck. The lower cloud is a region of dynamical instability in the Venus atmosphere. The mechanism responsible for driving the Venus circulation remains unclear, although it seems likely that interactions between waves and the mean flow, initiated by absorption of sunlight in the cloud region, play a central role.

Titan

Like Venus, Titan's atmosphere is a massive one with a dense haze layer and slow rotation and may be driven by the same mechanism. But the chemistry of the Titanian and Venusian atmospheres could hardly be more different. Titan's atmosphere is composed mainly of nitrogen with a few percent of methane and other hydrocarbons and nitriles (molecules with H, C, and N). Titan's atmosphere is cold (about 94 K near the surface and 71 K at the temperature minimum near 40 km altitude). At those temperatures methane may condense near the temperature minimum but some infrared measurements from the Voyager IRIS experiment suggest that a methane cloud may not be present. If that is the case methane would be supersaturated near the temperature minimum. Supersaturation does not occur in the terrestrial atmosphere (with respect to water) but can be achieved in the laboratory under controlled conditions. It will be difficult to resolve this issue until the Huygen's Probe descends into Titan's atmosphere in 2004.

Photolysis of methane in the high atmosphere leads to formation of ethane and other hydrocarbon and nitrile molecules. Processing of these molecules by long-term exposure to sunlight and charged-particle bombardment from space eventually produces a polymer haze which covers the satellite and blocks the surface from view at visible wavelengths. This haze is very dark at ultraviolet wavelengths and becomes bright, with little absorption at red wavelengths. It is composed of aggregates of small particles whose mean radius is close to 0.066 microns.

Chemical models predict a number of haze and cloud layers deeper in the atmosphere, composed of more volatile hydrocarbons. Methane is the most volatile and may condense below the temperature minimum (altitude range 10–40 km). A little higher in the atmosphere ethane may form a condensation cloud. Less volatile hydrocarbons and nitriles are expected to form condensate layers at higher altitudes, including C_2H_2, C_3H_4, C_3H_8, C_4H_2, HCN, C_2N_2, HC_3N, C_4N_2 and many heavier hydrocarbons. Carbon dioxide and water ice particles are also possible. Of these, only HC_3N and C_4N_2 particles have been detected spectroscopically. Detection of many of them is made difficult by Titan's obscuring photochemical haze at higher altitude. The spectral

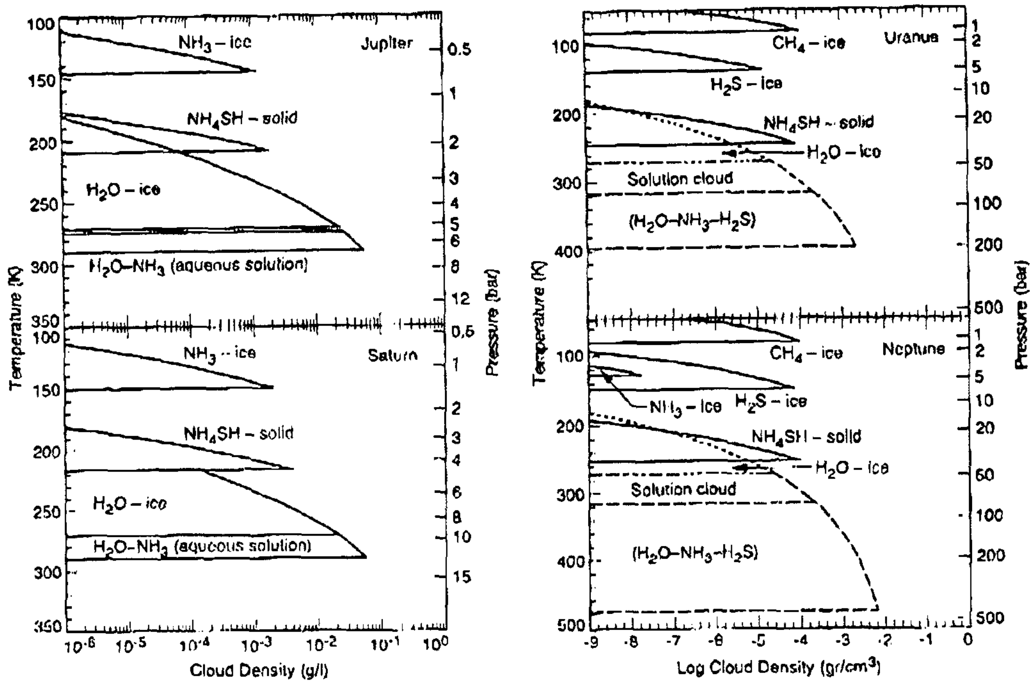

Figure 4. Thermochemical equilibrium models for the giant planet atmospheres indicate the vertical regions and compositions of ices expected to form clouds. Within these vertical regions actual cloud locations and densities are determined largely by atmospheric dynamics and microphysical processes. (Figures for Jupiter and Saturn were constructed from models by S K Atreya and M Wong, based on S K Atreya and P N Romani (1985) *Planetary Meteorology* ed G E Hunt (Cambridge: Cambridge University Press) pp 17–68. Those for Uranus and Neptune were first published by I de Pater *et al* (1991) *Icarus* 91 220–233, © Academic Press.)

signature of C_4N_2 (dicyanoacetylene) ice was seen by the Voyager infrared spectrometer only in the polar haze of Titan. Analysis of these observations reveals that (1) ice particle mean radius is near 5 μm, and (2) the ratio of condensate to vapor mole fraction as inferred from the data is about 100 times more than expected from steady-state equilibrium of the constituents, accounting for creation of the vapor at high altitudes from photochemical production, and depletion of the vapor and condensate at low altitudes due to condensation and sedimentation of particles. The large disequilibrium ratio is probably a result of seasonal variation of photochemical destruction of vapor at high altitude and high latitude working in conjunction with a significant thermal time lag deeper in the atmosphere due to long thermal time constants.

There is almost no contrast on Titan at visible wavelengths apart from a hemispheric north/south reflectivity contrast which reverses over a several-year period as Titan responds to seasonal changes in insolation. There is a corresponding hemispheric difference in particle size in the upper haze which in turn is related to a hemispheric-scale rising and sinking motion which responds to seasonal change. Atmospheric aerosols contribute significantly to the heat balance in the stratosphere through their strong absorption of sunlight and therefore are important to the energy balance and circulation.

The giant planets

All of the giant planets Jupiter, Saturn, Uranus and Neptune have deep atmospheres composed mainly of hydrogen and helium with trace amounts of cloud-forming molecules water, ammonia (NH_3), ammonium hydrosulfide (NH_4SH), hydrogen sulfide (H_2S) and methane (CH_4). All of these except methane can condense in the atmospheres of Jupiter and Saturn. The atmospheres of Uranus and Neptune reach sufficiently cold temperatures near the temperature minimum at 0.1 b pressure to condense methane. Condensate clouds form in layers with the most volatile forming at higher altitudes where the temperatures are cooler.

Our ideas about composition are based on a combination of observations from the ground and spacecraft together with models of chemical reactions at the temperature and composition of the atmosphere. So far all of our measurements, except those from the Galileo probe which entered Jupiter's atmosphere, are made remotely with instruments from the Earth or on spacecraft. The Galileo probe sampled a part of Jupiter's atmosphere that is thought to be depleted in condensable

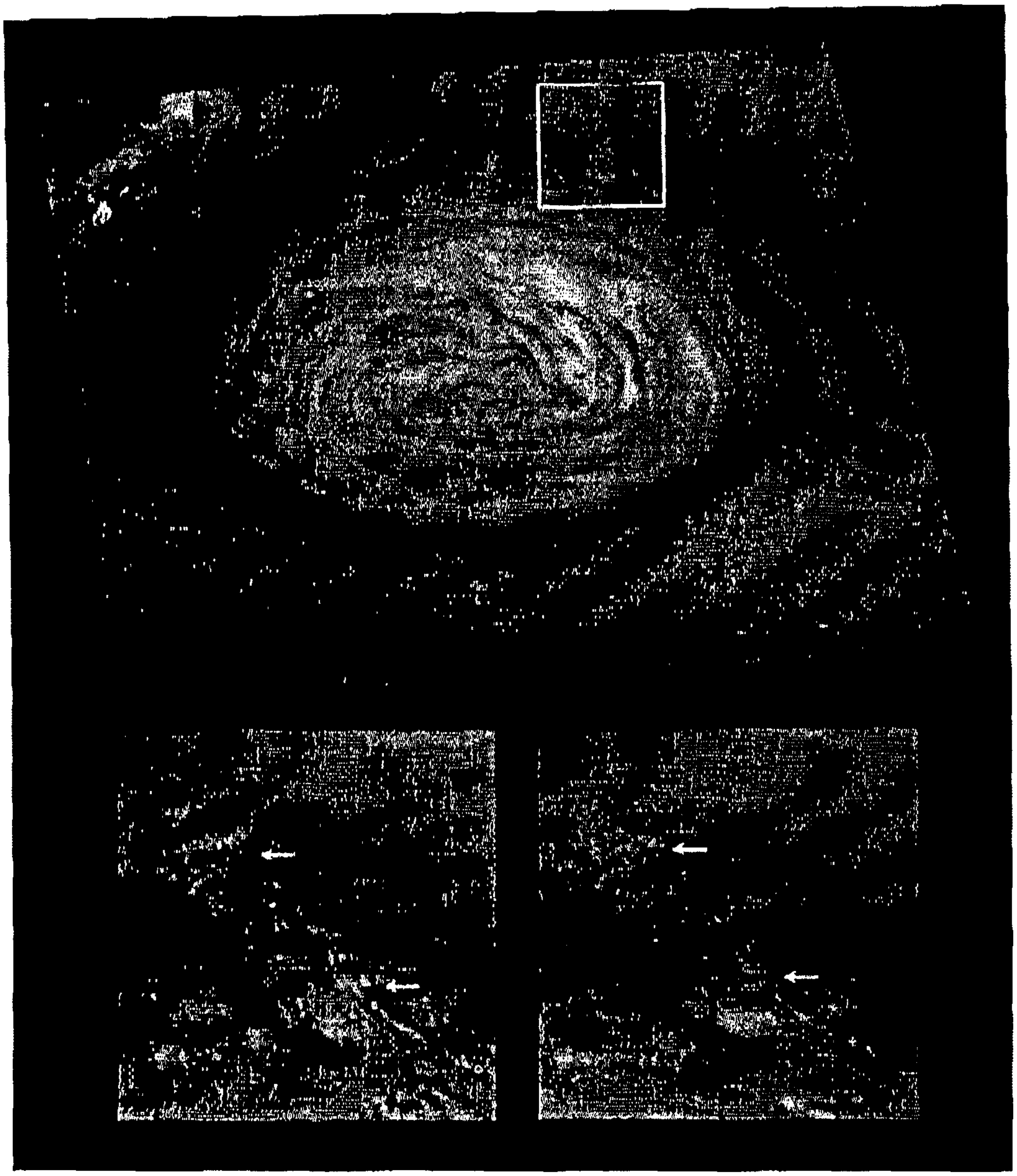

Figure 5. Jupiter's Great Red Spot and environs as seen by the Galileo Solid State Imager in 1996. The Great Red Spot centered in the top panel rotates counterclockwise. The embedded images shown in the two bottom panels reveal small puffy clouds about 50 km in diameter, possibly analogous to large terrestrial cumulus clouds. The time difference between the two bottom panels is 70 min.

molecules, much like a desert region on the Earth, and so the probe measurements do not tell us about the global properties of clouds and cloud-forming constituents.

As a starting point in understanding the vertical locations and compositions of clouds we rely on thermochemical equilibrium models which make predictions from measured or inferred chemical abundance in the deep atmosphere, the pressure and temperature as measured by a variety of instruments, and knowledge of the chemical thermodynamics of the available molecules. This exercise can tell us at what altitudes to expect clouds and what their composition should be but it is not adequate for predicting the number densities of cloud particles at a given location because other processes such as atmospheric dynamics and cloud particle microphysics determine those quantities.

The cloud forming molecules mentioned above are observe to be or are predicted to be a factor of two or more abundant than they would be for a mix of solar atmosphere material at the same temperature and pressure. The enhancement of 'solar' abundance increases from Jupiter to Saturn to Uranus and Neptune, reflecting the fact that the larger planets were able to retain more of the light elements hydrogen and helium during their formation. An increase in the amount of available condensable molecule will result in cloud formation at a deeper level where the temperatures are warmer.

Predicted cloud locations for the four giant planets are shown in figure 4. Jupiter and Saturn form one pair with similar cloud types, while Uranus and Neptune, which are colder, form a second. A water–ammonia solution cloud is predicted to form at pressure levels starting near 8 b in Jupiter's atmosphere and 15 b in Saturn's atmosphere. At higher altitudes (lower pressure and temperature) are clouds of ammonium hydrosulfide and ammonia ices. The topmost cloud in both cases is ammonia ice. A spectral signature for ammonia ice was mysteriously not seen until recently in near-infrared spectra from the European Infrared Space Observatory (ISO) and the Galileo NIMS instrument. Spectral signatures of ices in the other clouds have not been observed. One of the Galileo Probe experiments detected particles near the 1.6 b level in Jupiter's atmosphere whose composition could be either ammonium hydrosulfide or water. It did not see a water cloud at the pressure levels where thermochemical equilibrium models predict, probably because water in the region it sampled is depleted due to a downwelling of dry air from the cold upper troposphere. It is not known how extensive a deep water cloud may be on any of the giant planets.

Uranus and Neptune are cold enough to condense methane which forms the top cloud in those atmospheres. The next-deeper cloud, at a few bars pressure, is probably H_2S ice but may contain some ammonia as well. At deeper levels (10 to a few hundred bar pressure) are NH_4SH and water clouds.

The visibility of clouds varies markedly among the giant planets. Jupiter's atmosphere is filled with white-yellow clouds and darker yellow-brown clouds with a few regions that are more red (the Great Red Spot) or gray (the hot-spot regions where upwelling infrared radiation at 5 microns wavelength can be seen). Jupiter's Great Red Spot is a large (about 3 times the size of the Earth) oval rotating in the anticyclonic sense (opposite to terrestrial storm systems). It has been observed for more than a century and probably owes its stability to the shear of the east–west zonal jets in which it is embedded. It is shown in figure 5.

All of the ices mentioned above are white at visible wavelengths. If these were the only cloud constituents Jupiter would appear as a featureless white ball. The colors and contrasts are due to a coloring material whose origin and composition is uncertain. Candidate materials include compounds of hydrogen bonded to sulfur, nitrogen and carbon (hydrocarbons) created by photolysis in the upper troposphere or by bombardment from high-energy charged particles precipitating from the magnetosphere. The latter process is almost certainly responsible for the formation of polar stratospheric hazes in the stratospheres of Jupiter and Saturn.

Cloud contrasts are subdued for Saturn and almost absent for Uranus. These planets as well as Neptune have deep cloud structures which reduce contrast and block upwelling thermal radiation. Contrasts are dominated by the jet structures, although there is not a one-to-one correspondence between cloud reflectivity and wind speed and direction. Saturn shows seasonal variations in cloud altitude. These result from solar heating of the upper atmosphere which influences the static stability and cloud altitude. These effects may well be occurring as well on Uranus and Neptune but seasonal changes for those planets occur on timescales long compared to our ability to observe them. Individual ovals and spots do form in the Saturn atmosphere. They can be seen most easily in contrast-enhanced images (figure 6).

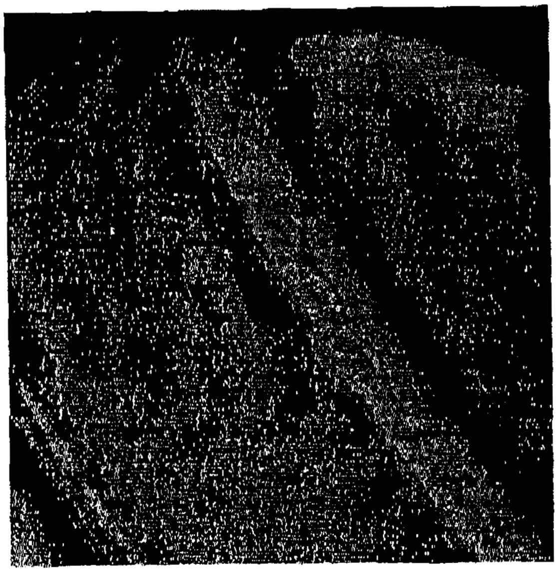

Figure 6. A dark oval and many smaller features can be seen embedded in the bright-dark cloud bands which line up with the jet streams in Saturn's atmosphere. A dark, kinked curve called the ribbon feature is centered in the bright band at 47° north latitude, the location of a high speed (150 m s^{-1}) jet. Cloud contrasts serve as markers of the wind and of the jet instabilities. This image was obtained by the Voyager 2 Imaging Subsystem in 1981.

The Voyager spacecraft viewed Uranus at a time when only one hemisphere was illuminated by the Sun. Only a few low-contrast cloud features were seen against an almost uniform thick cloud cover. More

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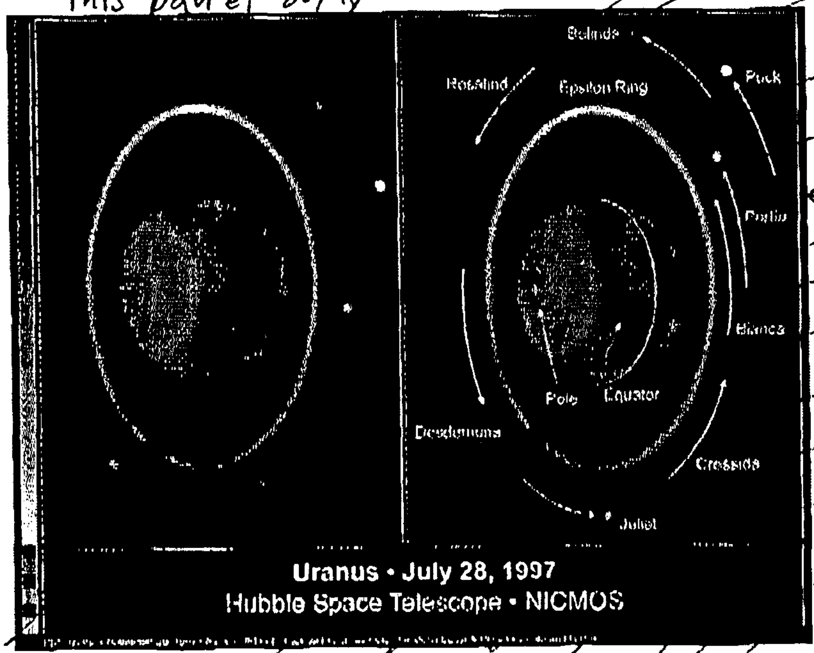

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Figure 7. Near-infrared images obtained by the NICMOS camera on the Hubble Space Telescope provide the best views of clouds in the Uranus atmosphere. The entire planet is covered by clouds but the south polar region is covered by a relatively high, thick cloud layer and appears bright in this view. Small clouds, newly discovered in this image taken in 1997, appear in northern low latitudes, just above the terminator. The rings and 8 of the uranian satellites are also visible.

recently the near-infrared camera on the Hubble Space Telescope photographed a number of clouds in the opposite hemisphere (figure 7).

A number of cloud types were seen during the close Voyager flyby of Neptune in 1989. Several large ovals were seen. The largest of them was named the Great Dark Spot (figure 8). Like Jupiter, some coloring constituent of uncertain origin and composition is responsible for cloud contrast and color. These ovals move around and oscillate in longitude. The aspect ratio and tilt of the long and short axes of the ovals also oscillate. These oscillations can be understood with models that take into account the vorticity of the spot, its depth in the atmosphere, and the wind shear in which it is embedded.

Other types of clouds were seen in the Neptune atmosphere which are reminiscent of cirrus clouds and lee-wave clouds seen high in the terrestrial and Martian atmospheres. They are striated, they evolve rapidly with time (too rapidly to use as tracers of wind) and some of them form clumps that are tied to and overlay the larger ovals. The White Companion to the Great Dark Spot is the prime example of this. It was seen even in ground-based images in one of the methane absorption bands sensitive to high clouds. It can be seen in figure 8. These clouds are probably composed of methane ice, with the underlying thick cloud bank being H_2S ice.

Cloud microphysics

Cloud microphysics is the study of processes that govern cloud particle formation and evolution on the microscopic scale. It addresses such questions as 'What conditions are required for clouds to form? How rapidly do particles grow? What controls the particle size distribution?' The study of cloud microphysical processes goes beyond the microscopic. A broader goal is to understand the underlying processes which govern cloud structure and dynamics over large scales. A considerable amount of work has been invested in answering these questions for terrestrial clouds where *in situ* measurements can be made and coupled with laboratory and theoretical investigations. There has been some attempt to understand the microphysics of clouds on the other planets, although the observational constraints are much weaker.

Condensate particles can form either by direct condensation from supersaturated vapor or by condensing on a pre-existing foreign particle (dust or sulfate aerosol, for example). These are called homogeneous and heterogeneous nucleation, respectively. Homogeneous nucleation begins when molecules in the vapor phase combine to form a small cluster which can serve as a seed nucleus. The cluster molecules may evaporate, or more molecules from the vapor may condense, depending on which outcome is favored by thermodynamics.

Figure 8. Neptune's Great Dark Spot (GDS) is the large dark oval to the left of center in this 1989 image by the Voyager Imaging Subsystem camera. The Bright Companion cloud forms at higher altitudes at the southern edge of the GDS. Several other bright clouds downstream (to the right) of the GDS and another large oval are also visible.

The Gibbs free energy is the thermodynamic quantity which controls particle growth or evaporation. Gibbs free energy depends on two terms, particle surface area times surface tension plus particle volume times KT times the natural log of the vapor pressure divided by the saturation vapor pressure, or

$$\Delta G = 4\pi a^2\sigma - \tfrac{4}{3}\pi a^3 n_l KT \ln(e/e_l).$$

In the above equation ΔG is the change in Gibbs free energy associated with the formation of a particle of radius a, σ is the surface tension of the liquid, n_l is the number density of molecules in the liquid, K is the Boltzmann constant, e is the vapor pressure and e_l is the saturation vapor pressure at temperature T.

A plot of ΔG as a function of radius a reveals that the Gibbs free energy for particle formation is always positive for vapor pressure less than or equal to the saturation vapor pressure. This is thermodynamically unfavorable and any particle which may exist initially will evaporate. When the vapor pressure is higher than the saturation vapor pressure the Gibbs free energy becomes negative at some particle radius. There is a critical radius, a_c, where condensation onto the particle surface reduces the Gibbs free energy and the particle will grow by condensation.

Under normal circumstances in the terrestrial atmosphere it is extremely difficult to grow a particle up to the critical radius because the ratio of vapor pressure to saturation vapor pressure is never very high. A much more common initiation of the growth process depends on the existence of cloud condensation nuclei (CCN) which may be composed of small dust or sulfate particles on Earth. A wide variety of CCN particle compositions may be present, but only a small fraction of them are conducive to growth. Particles whose surface structure is similar to that of water or ice (such as silver iodide crystals used for cloud seeding) make good CCN. Another class of particles which make even better CCN are hygroscopic sulfates and nitrates. An abundance of small CCN leads to an abundance of small droplets. Conversely, in an environment with few CCN, few water droplets will form, but the ones that do will take advantage of the available vapor to grow to relatively large size. Images of the ocean surface under some conditions reveal ship tracks as trails of small cloud particles whose formation was initiated by an abundance of CCN in the exhaust plumes of the ships.

Condensation alone is insufficient to grow particles in clouds to the point of precipitation over the coarse of a few hours. Another mechanism, growth by collision and merging of drops (coalescence) or sticking of ice particles (coagulation), produces much more rapid growth when the particles become large enough (about 20 μm radius) that sedimentation velocities become important. The largest particles sediment faster than the smaller ones, and collide with other particles as they descend through the cloud. This behavior leads to a process which can rapidly grow large (up to about 2 mm) particles. Even larger particles can form in updrafts or parcels which cycle between updrafts and downdrafts.

These ideas introduce the interplay between cloud microphysics and vertical and horizontal winds. Another coupling is between radiation and clouds. At the top of the cloud layer the cloud cools by emitting thermal radiation to space. This cooling in turn feeds a circulation pattern with sinking cool air replaced by rising warmer air from below and within the cloud. Thus the three major physical processes (cloud microphysics, atmospheric dynamics, and radiation) are all coupled, and this coupling must be taken into account in cloud formation/evolution models.

Cirrus clouds form near the top of the troposphere where the temperatures are cold (some 40 °C lower than the freezing temperature of water). Clouds are supplied with vapor from the tops of large convective systems carried horizontally by the wind shear. Both liquid and ice can exist, with the liquid supercooled by more than 30 °C. Ice crystals can grow to relatively large sizes (on the order of 100 μm) as they descend. Ice crystals forming at a variety of temperatures produce a wide variety of crystal habits, but the dominant forms are hexagonal. Typical crystal angles are 120° and 90°. These lead to halo features, the most common at a scattering angle of 22°. Flat plates tend to orient in one direction as they fall due to their aerodynamical profile. Particle orientation leads to certain types of halos.

Microphysical models of Venus, Mars, Titan, and the giant planets

Venus

Our knowledge of the Venus cloud structure is considerable, thanks to extensive measurements from multiple instruments on several probes which descended though the atmosphere, as well as remote spacecraft and ground-based instruments. Models of the cloud microphysics must take into account the coupled chemical composition of the particles and gas (both change with altitude), photochemical processes at the top of the atmosphere, the temperature profile of the atmosphere, and vertical transport due to eddy motions and particle sedimentation.

Microphysical models attempt to reproduce the observed particle chemistry (sulfuric acid/water solution whose concentration varies with altitude as determined by temperature) and the size distribution and number density of the particles which also vary with altitude. Recalling that there are three principal cloud layers in the Venus atmosphere, the topmost is governed by photochemical processes which act on sulfur dioxide and water to produce a sulfuric acid cloud. The top cloud is close to steady state with little temporal variation. Particle growth matches loss by sedimentation. Particle growth is governed by the available sulfate produced by photochemistry. Sulfur dioxide is supplied by vertical transport from below the clouds. A bi-modal size distribution is observed in the top cloud with one mode having mode radius 0.3 μm, and the other with mode radius 1 μm.

The lower and middle clouds form by condensation from existing vapor rather than by photochemistry which drives particle formation in the top cloud. Two vapor constituents (H_2SO_4 and H_2O) are present in varying amounts. Small particles are present below the base of the lower cloud and these can serve as condensation nuclei. Model simulations show that the two most important parameters of the model are the vertical transport, as characterized by an eddy diffusion profile which is a function of altitude (it reaches a peak at 54 km altitude in the model), and the nucleation mechanism. The nucleation mechanism is thought to be a combination of heterogeneous nucleation on insoluble cores and an activation mechanism on soluble (hygroscopic) cores. A numerical model accounts for the balance in vapor pressures of H_2SO_4 and H_2O as a function of temperature, the supply of vapor via eddy diffusion, loss rates due to sedimentation, and continuity of particle mass as particles grow. The model reproduces the observed tri-modal particle size distribution. The smallest particles (less than 0.6 μm) are the insoluble cores. The largest particles (typically 3-4 μm radius) are those which nucleate near the top of the cloud. As they fall they grow by collision and condensation, becoming larger at lower altitudes.

Mars

Water molecules condense on dust nuclei in the Martian atmosphere to form water ice clouds. The water abundance is not high and so ice condensation requires both cold temperatures and availability of dust condensation nuclei. At very cold temperatures carbon dioxide can condense on the water ice particles.

Images from space and from the Viking and Mars Pathfinder landers have shown that ice cloud formation on Mars is highly variable. When Mars is farthest from the Sun the temperatures are colder and ice clouds are more extensive and more frequent. But even during the few weeks of the Mars Pathfinder mission cloud formation near the landing site was highly variable.

There are several major differences between ice cloud formation on Mars and the Earth. The water abundance in the Martian atmosphere is much less than that for Earth. As a consequence there are so few particles the coagulation process can be ignored, leaving nucleation, condensation and sedimentation as the factors which determine cloud formation and particle size distribution. The smallest particles are the same size as the condensation nuclei. The ability of Martian dust particles to serve as nucleation sites is highly uncertain because not much is known about the mineralogy, which has a strong effect on nucleation. Clay minerals might be present, and they typically are efficient nucleators. Other mineral types are inefficient. One way to account for the uncertainty in modeling this process is to make the contact parameter a parameter of the microphysical model. The energy associated with ice particle formation is proportional to the factor $(2+m)(1-m)^2$ where m is the contact parameter. Values of m close to 1 (e.g. for silver iodide, for example) reduce the energy of formation leading to rapid nucleation. Typical terrestrial soil particles have m near 0.4.

Microphysical models which employ the temperature profile as determined by the Mars Pathfinder instruments find ice cloud formation in two layers. The highest is in the altitude range 30–50 km. A second layer forms at the temperature minimum near 10 km altitude. Competition between growth by nucleation and condensation and loss by sedimentation defines the size distribution. Particles in the upper layer have mean radius near 1.5 μm, whereas those in the lower layer have mean radius near 2.5 μm.

Titan

As is the case for the Earth, Venus, and the giant planets, clouds or haze in the stratosphere form as a result of photochemical processes, whereas those in the troposphere form from condensation. At the deepest level there should be methane clouds. Other condensate clouds, possibly with a variety of compositions, may form at intermediate levels.

Methane cloud formation near the temperature minimum (below 40 km altitude) is highly uncertain. The Voyager infrared spectra have been interpreted by some to imply that methane is highly supersaturated near the temperature minimum. This cannot occur in the presence of a substantial cloud, and so would imply that condensation occurs only rarely, forming large ice (or liquid in the lowest few km) particles which fall rapidly to the surface (rain without clouds). That scenario was proposed prior to the interpretation of high global supersaturation of methane. Titan and the Earth may differ significantly in terms of the number of condensation nuclei available to initiate particle formation. On the Earth there are numerous CCN mixed up from the surface. On Titan the only CCN available may come from slow sedimentation of the overlying photochemical haze and from other condensates. The number density from that source is thought to be quite low compared to that for the Earth. Low CCN density would lead to fewer particles, but those that form can grow by condensation to large size (radii greater than 50 μm) because their formation does little to deplete the available vapor. Both microphysical models and recent ground-based near-infrared spectra imply patchy and variable clouds of large methane ice or liquid particles which form at an altitude near 15 km.

Titan's stratospheric photochemical haze is composed of complex hydrocarbons and nitriles. The starting point for this process is the photolysis of methane and nitrogen high in the atmosphere (higher than 300 km altitude). Although the process is slow, over geologic time enough methane should have been processed to generate 100 m thick surface deposits of liquid ethane and solid organic material, provided a surface reservoir of methane has been available to replenish that which is destroyed over billions of years. The haze particles are undoubtedly complex organics and nitriles, although not enough is know to be more specific regarding the composition.

Microphysical models for Titan's stratospheric haze lump the chemical processes leading to formation of condensable organics into one adjustable parameter, the mass production rate of aerosol-forming molecules at the top of the haze layer. Nucleation is assumed to be initiated by formation of small clusters of molecules which grow through collisions. Models include particle charging by UV and cosmic ray events. Charge is a free parameter (number of electrons per unit particle radius) and serves to inhibit growth by coagulation. Traditional microphysical models assumed the particles remain spherical as they grow. This would be expected if the particles are liquid. More recent models incorporate laboratory results and theoretical predictions which favor solid particles. As solid particles collide they stick together to form aggregates. As the aggregates collide with each other they form larger aggregates which have a fractal nature. Cluster–cluster aggregates have fractal dimension close to 2 (versus spheres which have fractal dimension 3). Near the top of the haze layer (~400 km) the growth process is via molecules which stick to individual particles. The individual particles grow to some size limit determined by the pressure. Both theory and observation indicate the individual particles, or monomers have radii near 0.066 μm. Mutual collisions among the monomers give rise to clusters and to cluster–cluster aggregates as the particles settle. The cluster aggregate idea can explain the combination of strong linear polarization in light scattered near 90° scattering angle and the strong scattering of light in the forward direction.

Giant planets

Microphysical studies of the condensate clouds in the tropospheres of the giant planets rely on the familiar principles which describe growth by condensation, coagulation, and coalescence and loss by evaporation and sedimentation. However, these models are extremely crude because the number and composition of potential cloud condensation nuclei are unknown. Furthermore cloud formation depends strongly on atmospheric dynamics which are not taken into account. There are no *in situ* measurements except for the Galileo probe which found few particles in its descent path through a volatile-depleted patch of Jovian atmosphere. Some microphysical models predict that the methane clouds on Uranus and Neptune are 10–100 times more massive than any clouds on Earth. However, the observations show very little methane cloud mass. Observational evidence for the water cloud is lacking, although higher clouds interfere. The ammonia cloud near the top of the troposphere on Jupiter and Saturn is predicted from microphysical models to be a weakly precipitating cloud similar to terrestrial cirrus, and observations are consistent with that idea.

Coupled photochemical/cloud microphysical models are able to account for the optical depth and size distribution of hydrocarbon haze particles in the stratospheres of Uranus and Neptune, provided the mass production rate and particle charge are adjustable parameters. The models account for particle sizes (all submicron) and vertical profiles as derived from Voyager data. Eddy diffusion transports methane to the upper atmosphere where photochemical processes lead to formation of diacetylene, acetylene, and ethane ice particles which condense near 0.1 mb, 2.5 mb, and 14 mb, respectively. As the particles fall to pressures greater than 600 mb they evaporate as the temperature rises. Organic polymers can also form, probably via solid-state photochemistry within the original ice particle during the settling lifetime. This process can account for the weak absorption seen in reflected sunlight.

Bibliography

Grinspoon D H, Pollack J B, Sitton B R, Carlson R W, Kamp L W, Baines K H, Encrenaz Th. and Taylor F W 1993 Probing Venus's cloud structure with Galileo NIMS *Planet. Space Sci.* **41** 515–42

Houze R A 1993 *Cloud Dynamics* (New York: Academic)

Kahn R 1984 The spatial and seasonal distribution of Martian clouds and some meteorological implications *J. Geophys. Res.* 89 6671–88

West R A, Strobel D F and Tomasko M G 1986 Clouds, aerosols and photochemistry in the Jovian atmosphere *Icarus* 65 161–217

West R A, Baines K H and Pollack J B 1991 Atmospheric clouds and aerosols in the Uranian atmosphere *Uranus* ed J T Bergstralh, E D Miner and M S Mathews (Tucson, AZ: The University of Arizona Press) pp 296–324

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